

# Hydro and Hydro-Mechanical Modelling of Ventilation Test in Clayey Rocks

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**Abstract.** Hydro and hydro-mechanical numerical modellings are performed in order to acquire a better understanding of clayey rock behaviour and transfers occurring during an *in situ* ventilation test. The test is performed in an experimental gallery that is part of an underground research laboratory. A biphasic flow model for unsaturated soil and an elasto-plastic constitutive law are used for the host formation. The models include exchange condition of fluid mass, anisotropy and the excavation damaged zone around the gallery. Finally, the ventilation test is reproduced and the model is calibrated based on the matching between numerical results and experimental measurements.

**Keywords:** unsaturated soil, excavation damaged zone, numerical modelling, radioactive waste, biphasic flow model.

## 1 Introduction

Long-term repository of radioactive waste in deep argillaceous geological media needs a good understanding of the host formation behaviour. Underground

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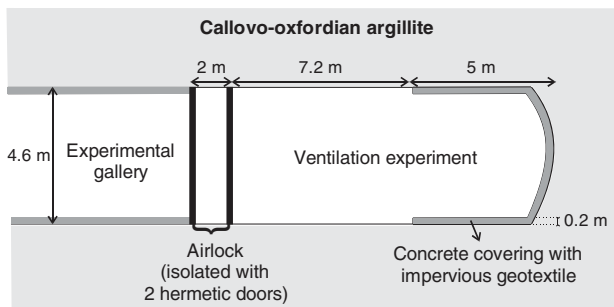
research laboratories (URL) have been developed in Europe (Delay et al. 2007, Neerdael & Boyazis 1997) and in America (Rutqvist et al. 2005) to study the feasibility of a safe repository in low permeability media. In these laboratories, *in situ* experiments are performed to characterise the formation.

During the excavation of galleries composing underground structures for radioactive waste repository and URL, the rock mass close to the gallery is damaged and its permeability is modified. Considering the safety function of the formation and the need of low permeability, the behaviour of the excavation damaged zone (EDZ) is a major issue (Blümling et al. 2007).

## 2 In Situ Ventilation Test

Ventilation in galleries and drainage may modify the structure and the size of the damaged zone. A ventilation test (SDZ) is realised by the French national radioactive waste management agency (ANDRA) in the Meuse/Haute-Marne URL located in Callovo-Oxfordian claystone (Cruchaudet et al. 2010a). The aim is to characterise the influence of controlled ventilation imposed in an experimental gallery on the behaviour of the rock mass and the damaged zone.

The experimental zone is located at the end of an experimental gallery (GED) and is composed of an airlock, a test zone without covering and, at the end, a test zone with covering. Concrete slab and wall covering are present in the gallery. The geometry of the experimental zone is presented in fig. 1. During the test, ventilation is performed in the gallery. After 230 days of ventilation the airlock is closed, the ventilation is stopped in the experimental zone and the exchanges between this zone and the gallery occur through the damaged zone. Several *in situ* experimental measurements are realised during the test and exhibit the hydro-mechanical behaviour of the rock around the gallery. Numerical modelling is performed in order to reproduce the experimental results and acquire a better understanding of transfers occurring during the test.



**Fig. 1.** Geometry of the experimental zone of the ventilation test SDZ.

3 Biphasic Flow and Mechanical Models

A biphasic flow model is used to reproduce water and air transfers in partially saturated porous media. This model manages a liquid phase composed of liquid water and dissolved air and a gaseous phase which is an ideal mixture of dry air and water vapour. It takes into account the following phenomena: advection of liquid phase modeled by Darcy’s flow, diffusion in the gaseous phase and diffusion of dissolved air in water represented by Fick’s law. The density of dissolved air is proportional to the density of dry air by Henry’s law. More details about the biphasic flow model are available in (Collin et al. 2002, Gerard et al. 2008a). The retention curve and the water relative permeability curve are given by the van Genuchten’s model (van Genuchten 1984).

The mechanical behaviour of concrete is linear elastic. The constitutive mechanical law for the clayey rock is a non-associated linear elastic-perfectly plastic model with a Van Eekelen yield surface. This model is written in terms of the Bishop’s definition of effective stress (Nuth & Laloui 2008).

A synthesis of the main Callovo-Oxfordian claystone parameters available in the literature is presented in (Charlier et al. 2012). These parameters were obtained from laboratory testing. The hydraulic and mechanical parameters used for argillite and concrete are defined in Table 1 and Table 2.

Table 1. Hydraulic parameters for argillite and concrete.

		Argillite	Concrete
$K_{w,sat,hor}$	Horizontal intrinsic water permeability (m <sup>2</sup> )	$4 \times 10^{-20}$	$1 \times 10^{-18}$
$K_{w,sat,vert}$	Vertical intrinsic water permeability (m <sup>2</sup> )	$1.33 \times 10^{-20}$	$1 \times 10^{-18}$
$\Phi$	Porosity (-)	0.18	0.2
$m$	van Genuchten coefficient (-)	0.33	0.35
$n$	van Genuchten coefficient (-)	1.49	1.54
$P_r$	van Genuchten air entry pressure (MPa)	15	2
$\tau$	Tortuosity (-)	0.25	0.25

Table 2. Mechanical parameters for argillite and concrete.

		Argillite	Concrete
$E_0$	Young’s modulus (MPa)	4000	30000
$\nu_0$	Poisson’s ratio (-)	0.3	0.3
$c$	Cohesion (MPa)	3	-
$\phi$	Friction angle (°)	20	-
$b$	Biot’s coefficient (-)	0.6	1
$\rho$	Density (kg/m <sup>3</sup> )	2300	2300

## 4 Hydraulic Boundary Condition for Exchanges at Gallery Wall

A nonclassical boundary condition with water and vapour exchanges has been developed in order to model the exchanges between the cavity and the rock (Gerard et al. 2008b). This condition implies that two modes of exchange can occur in ventilated cavities (Ghezzehei et al. 2004). The total water flow boundary condition is expressed as the sum of a seepage flow and a vapour exchange flow:

$$\bar{E} = \bar{S} + \bar{q} \quad (1)$$

The seepage flow occurs if pore water pressure in the gallery wall rock is larger than cavity air pressure. It is introduced in a finite element code by the function:

$$\begin{cases} \bar{S} = K(p_w^\Gamma - p_{atm})^2 & \text{if } p_w^\Gamma \geq p_w^{air} \text{ and } p_w^\Gamma \geq p_{atm} \\ \bar{S} = 0 & \text{if } p_w^\Gamma < p_w^{air} \text{ or } p_w^\Gamma < p_{atm} \end{cases} \quad (2)$$

with  $p_w^\Gamma$  the pore water pressure in the rock formation,  $p_w^{air}$  the water pressure corresponding to the relative humidity in the cavity air,  $p_{atm}$  the atmospheric pressure and  $K$  a penalty coefficient for seepage.  $p_w^{air}$  is obtained using Kelvin's law implying that the total suction is equal to the matric suction, without considering osmotic suction.

The vapour exchange mode assumes the existence of a boundary layer on the cavity porous surface (Ghezzehei et al. 2004). It occurs if a difference between vapour densities exists between the rock and the cavity air (Ben Nasrallah & Pere 1988):

$$\bar{E} = \alpha(\rho_v^\Gamma - \rho_v^{air}) \quad (3)$$

with  $\rho_v^\Gamma$  and  $\rho_v^{air}$  the vapour density respectively in the rock formation and in the cavity and  $\alpha$  a vapour mass transfer coefficient.

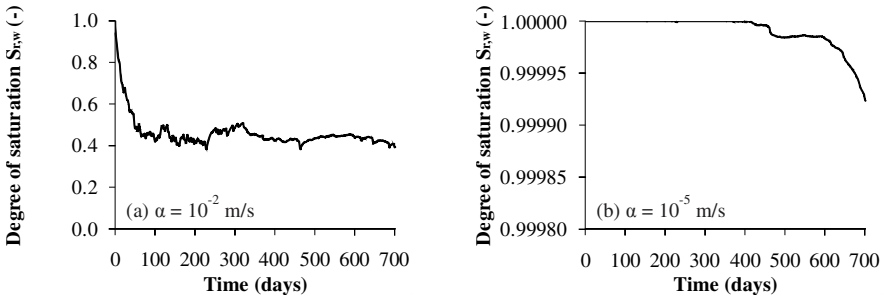
## 5 Numerical Results

To highlight the effect of gallery ventilation on the rock mass and the damaged zone, two modelling cases are considered. Firstly, only the fluid transfer is modeled, secondly a hydro-mechanical coupling is realised. During ventilation, the temperature and relative humidity are measured in the gallery. They are imposed on the gallery wall by Kelvin's law and through the boundary condition.

A two-dimensional plane strain state, a two-dimensional axisymmetric state and a three-dimensional state models are realised taking into account only water transfers. The first model allows a good representation of the damaged zone and the anisotropic characteristics. The second provides a good representation of the axial exchanges between the SDZ experimental zone, the gallery and the damaged zone. The third allows taking into account all these aspects.

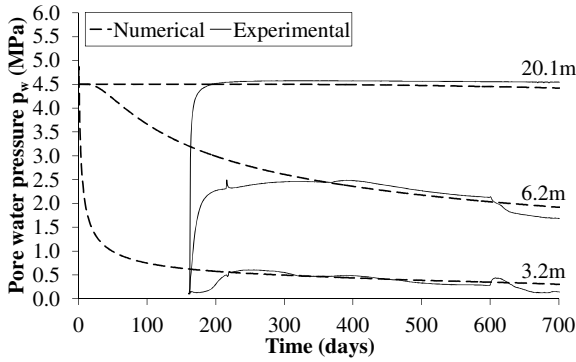
The damaged zone is *a priori* defined in the models with a higher intrinsic permeability than the clayey rock ( $K_{w,sat,hor}=4\times10^{-17}\text{m}^2$ ,  $K_{w,sat,ver}=1.33\times10^{-17}\text{m}^2$ ) and an elliptical extension (2.7m horizontally and 3.7m vertically) based on *in situ* fractures measurements. The models are implemented in the finite element code Lagamine with an isothermal condition  $T=293^\circ\text{K}$ , a constant gas pressure equal to the atmospheric pressure and an initial pore water pressure of 4.5MPa.

Numerical results highlight that the vapour mass transfer coefficient  $\alpha$  has a significant influence on the reproduction of SDZ experimental measurements of pore water pressure. Those measurements are performed in boreholes located around the experimental zone at different distances from the gallery wall with a first measure corresponding to 160 days of calculation. A high value of this coefficient implies important exchanges between the rock mass and the cavity air. In this case, the drainage is overestimated in the rock mass and the damaged zone is highly desaturated. A low value implies low exchanges between the rock and the cavity, a very low desaturation of the damaged zone and provides a good matching with experimental measurements. The rock desaturation at the gallery wall for a high and a low values of this coefficient is presented in fig. 2. Because the water permeability of the EDZ is high, its degree of saturation is similar to that of the gallery wall. The best matching with experimental measurements is obtained with  $\alpha=10^{-5}\text{m.s}^{-1}$  and is presented in fig. 3 for the three-dimensional state model.

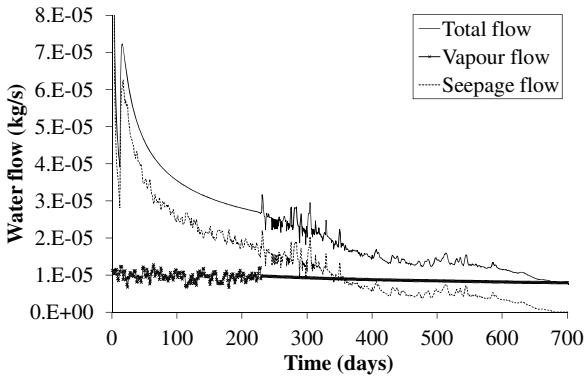


**Fig. 2.** Rock desaturation at gallery wall for (a) a high and (b) a low values of the vapour mass transfer coefficient (two-dimensional plane strain state modelling with only fluid transfer).

For the chosen vapour mass transfer coefficient, the results obtained with the axisymmetric state model (hydraulic model) highlight that transfers take place in the damaged zone during the test. The water flows around the gallery are radially directed toward the SDZ cavity and longitudinally directed toward the experimental gallery after the airlock closure. The radial water flows through the gallery wall in the test zone without covering are presented in fig. 4: in the short term, the seepage is predominant but decreases rapidly, whereas in the long term, the vapour exchanges remain almost constant.



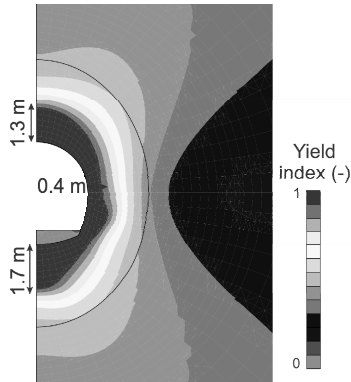
**Fig. 3.** Matching between numerical results and experimental measurements for a low vapour mass transfer coefficient at different distances from the gallery wall (three-dimensional state modelling with only fluid transfer).



**Fig. 4.** Evolution of the radial water flows through the gallery wall in test zone without covering and directed toward the cavity (two-dimensional axisymmetric state modelling with only fluid transfer).

A two-dimensional plane strain state model is also realised with a hydro-mechanical coupling taking into account the anisotropic stress state ( $\sigma_{hor,0}=15.6\text{MPa}$ ,  $\sigma_{vert,0}=12\text{MPa}$ ) and the excavation. The damaged zone remains *a priori* defined in the model. The objective is to compare the plastic zone obtained numerically with the damaged zone measured *in situ*. Using the set of parameters detailed previously, the evolution of the plastic zone extension occurs during the excavation and its final dimensions are about 0.4m horizontally, 1.3m and 1.7m respectively vertically upward and downward (fig. 5). The extension of the damaged zone based on mixed fracture (tension and shear) measurements is 0.5m horizontally, 1.7m and 2.0m respectively vertically upward and downward. The extension of the damaged zone based on high permeability measurements is 0.5m

horizontally, 1.1m vertically upward and downward. Details about those experimental measurements, performed by ANDRA, are available in (Cruchaudet et al. 2010b). The plastic zone observed numerically corresponds fairly to the experimental measurements of the damaged zone extension.



**Fig. 5.** Plastic zone extension obtained numerically at the end of the modelling. Yield index = 1: plastic domain, Yield index < 1: elastic domain (two-dimensional plane strain state modelling with hydro-mechanical coupling).

## 6 Conclusion

Numerical results show that it is possible to calibrate the models to obtain a satisfactory reproduction of the *in situ* experimental measurements. The vapour mass transfer coefficient used in the boundary condition has a significant influence on the results. It needs to be calibrated based on *in situ* experimental measurements. The adopted value is low and implies low transfers. It challenges the classical imposition at gallery wall of the suction corresponding to the relative humidity of the cavity air. This classical imposition involves a brutal transmission of air humidity to the rock and a significant desaturation. The development of a nonclassical boundary condition is therefore necessary. However, the adopted value of the transfer coefficient is lower than the one determined experimentally from convective drying tests performed on small samples (Gerard et al. 2010). A scale factor may explain this difference and should be considered in a particular study.

The results provide also a better understanding of the fluid transfer around the gallery and in the damaged zone during the test. The hydro-mechanical model exhibits a plastic zone extension similar to the *in situ* measurements but it doesn't provide information about the rock state within this zone. It would be necessary to validate the results with a more accurate modelling of the damaged zone and of the hydro-mechanical coupling occurring in it (Levasseur et al. 2009). Permeability is probably not homogeneous in the damaged zone and is probably dependent on a mechanical parameter such as the plastic deformation (Levasseur et al. 2010).

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